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University of Texas at El Paso
Department of Geological Sciences

Final Report

Grant Number F49620–92–J–0438

Lithospheric Profiles in the Southwestern U.S. Using Nevada Test Site Sources

Principal Investigators: G. Randy Keller, Diane I. Doser, Kate C. Miller

STATUS OF EFFORT

The University of Texas at El Paso (UTEP) geophysics group as been conducting a wide variety of geophysical studies in the southwestern U. S. which have involved the cooperation of numerous university and governmental groups. The objectives of this project were to use the results to investigate lithospheric structure and seismic wave propagation in the area. This final year of the project has been very active with the successful completion of a major seismic field project and continued progress on our efforts to obtain a good overall view of the geophysical properties of the region. In particular, our efforts have provided a much improved picture of lithospheric structure in the NTS region. The seismic field experiment was an ambitious effort which produced data out to offsets of greater than 1000 km.

ACCOMPLISHMENTS

Regional Studies

One focus of our effort involves workers from Los Alamos National Laboratory, the Phillips Laboratory, the U. S. Geological Survey, and the Air Force Weapons Lab with whom we have working to obtain data along a transect extending from the NTS area to White Sands Missile Range (WSMR) and eastward. This 1200km long transect spans the

Basin and Range, Colorado Plateau, Mogollon–Datil volcanic field, Rio Grande rift, and eastern Great Plains and provides a unique opportunity to examine deep structure and seismic propagation across a series of complex and active tectonic features. Shots at WSMR have been recorded to provide partial reversal of NTS sources which have been recorded in the past. We also have conducted receiver function studies, surface wave dispersion analyses, and refraction surveys to provide constraints on shallow structure along the transect. This year, the emphasis has been on conducting receiver function studies at locations in New Mexico, Texas, and Arizona. Data collection has gone slowly, and we have not had enough time to collect sufficient data to produce lithospheric models.

The conventional explosion of the Non–Proliferation Experiment at the NTS provided an opportunity to interface with a major seismic experiment targeting the Sierra Nevada Mountains. By cooperating with this experiment, we were be able to record a long profile extending westward from NTS across this mountain range and significantly add to the overall success of this large cooperative effort. A much improved picture of earth structure around NTS result has resulted, but our lack of knowledge of structure at NTS has been highlighted during this effort. The effects of the deep structure of mountain ranges on seismic waves is a major concern in efforts to monitor seismic events in many areas around the world and the Sierra Nevada were shown to have very little in the way of a crustal root.

Tomographic Study

We have completed a tomographic study of the Mojave desert – NTS area which focussed on detecting anisotropy. Data from the Caltech, University of California at Berkeley, University of Nevada at Reno, and U.S. Geological Survey networks in the region, as well as from the 1994 DELTA FORCE and the 1993 Southern Sierra Nevada Continental Dy-

namics seismic refraction experiments were analyzed. We developed software for tomographic analysis including the presence of anisotropy. Over 900 earthquakes and explosions yielded over 40,000 ray paths through the Mojave and Southern Basin and Range region.

The tomography algorithm employed in this study incorporates *a priori* information to add stability to the inversion, accounts for anisotropy, and includes data and model uncertainties. The equation solved in this inversion is unique because it includes the actual data, the *a priori* model, both data and model uncertainties, and the residual matrix between the observed and predicted travel times, which is minimized. Synthetic data investigations have shown overestimating the data and model uncertainties is better than underestimating them. The data uncertainty has a larger control on convergence criteria than model uncertainties.

The poor raypath coverage in the eastern Mojave, and the southern and central Basin and Range due to the lack of permanent stations in those regions prevented a more detailed tectonic analysis of these regions. However, this was still one of the more detailed three–dimensional tomographic studies of this region to date. This particular tomographic method is well–suited for a more detailed study of a smaller area. Smaller magnitude events could then be incorporated, perhaps substantially improving raypath coverage. A smaller study area with more data might also facilitate usage of a smaller block size. This would prevent "smearing" of velocities with depth and improve the resolution of the resulting tomographic images

Anisotropy developed at depths of 15 km and shallower using the one–dimensional model; however, no anisotropy developed at any level using the *a priori* starting model. Neither model developed anisotropy at depths below 15 km. This is in contrast to the fast

east–west direction in the Mojave observed by Hearn (1996). The azimuthal bias of events used in this study, the different algorithms employed, or the resolution of the different studies all may account for the contrasting results.

The velocities of the western Mojave appear to be similar to those of the Great Basin, in areas resolved with raypath coverage, although velocities of the Great Basin are a little lower. Only areas within the western and central Mojave and Great Basin can be resolved from 5–20 km depth for the one–dimensional model and 5–10 km depth for the *a priori* starting model. Higher velocities are present in the southeastern Mojave from 5–10 km depth. Basin and Range low velocities correlate well with areas of high heat flow (Sass *et al.*, 1994); however, the Mojave block has lower heat flow than the Basin and Range in areas with low velocities. The high velocities in the eastern Mojave exist in an area of the highest heat flow (>100 mW m^{-2}; Sass *et al.*, 1994).

At depths of 35–40 km for the one–dimensional model and 30–40 km for the *a priori* model, the Garlock fault appears to separate areas of low velocities of the central Basin and Range from higher velocities of the Mojave block. A wedge of lower velocities extends across the Garlock into the northeastern Mojave. Velocities in the southern Basin and Range are also lower than those of the Mojave block. The distribution of velocities correlates well with the heat flow results of Sass *et al.* (1994) at these depths. These velocity observations in the mantle reinforce the suggestions by other researchers that the Basin and Range is more active than the Mojave block. The contrasts in velocities across the Garlock also suggest that it may be a deep seated feature. Studies by Hearn (1986b) and Zhao and Kanamori (1992) report similar findings in their tomography studies.

The crustal observations in the Mojave are enigmatic. The velocity structure suggests that the crust between the Mojave block and the Basin and Range might be similar. Howev-

er, the correlations with heat flow and the shallower depth of seismicity in the Mojave than in the Basin and Range are opposite of what might be expected. Basement lithology may play a large role in determining a shallower depth of the seismogenic zone, given the present stress field in the Mojave. But this alone does not seem adequate to explain the shallower depth of seismicity in the Mojave block with lower heat flow than that of the Basin and Range.

We have been analyzing data from the DELTA FORCE experiment where a series of long profiles emanating from near NTS were recorded. One of these profiles (Line 1, Figure 1) lies along the NTS–WSMR transect, and others tie to recent experiments in the region (PACE, BARGE, NPE/SSCD). Thanks to the cooperation of the National Science Foundation, Caltech was able to obtain funding to enhance this experiment with another shot point. The end result of these efforts is a series of interlocking seismic profiles which should greatly enhance our knowledge of lithospheric structure and wave propagation in the NTS region.

The DELTA FORCE experiment

The DELTA FORCE experiment (Figure 1) consisted of setting a total of 474 seismic recorders [166 Refteks, 188 Seismic Group Recorders (SGR) and 120 Seismic Cassette Recorders (SCR)] along 3 line segments in a single deployment to record 4 explosive sources placed in drilled holes producing an approximate total of 1896 seismic traces. The recorders were deployed along a NNW–SSE line (Line 1) extending from Blythe, CA (Source 4) to Death Valley Junction (Source 2), NV, an E–W line (Line 2) extending from Death Valley Junction, NV through Kingman, AZ (Source 3) to north of Williams, AZ and a N–S line extending from the north rim of the Grand Canyon near Hurricane, UT (Source 1)

through Kingman, AZ to Lake Havasu, AZ. The shots were recorded in both profile and fan style. Line 1 is completely reversed, while line 2 is partially reversed from source 2 to source 3, and line 3 is partially reversed from source 1 to source 3. Line 1 extends along the Colorado River extensional corridor to the vicinity of Death Valley and parallels the transition between Basin & Range and the Colorado Plateau. Preliminary results suggest Pn arriving with a velocity of 7.8 km/s consistent with other previous studies. Pg is consistent with a velocity of 6.6 km/s. Crossover distance is ~140 km, consistent with a 30 km thick crust. There is no apparent dip in the record sections. Line 2 extends from the Basin and Range of Nevada, through the Transition Zone and into the Colorado Plateau of Arizona, although the orientation is not strictly perpendicular to the boundaries between provinces. Crossover distance from source 2 appears to be ~180 km. Line 3 extends from the edge of the plateau through the transition zone and into the Colorado river extensional corridor with an apparent crossover distance of ~140 km from source 1.

The DEEP PROBE experiment

Our major field effort this year was the DEEP PROBE experiment (Figure 2) which was undertaken in July and August in cooperation with Rice University and the Canadian LITHOPROBE project. As we move toward a Comprehensive Test Ban Treaty, it has become increasing clear that detailed knowledge of lithospheric structure is necessary to verification efforts. Key phases which are being used as discriminants (Pn, Pg, Lg, etc.) travel exclusively in the lithosphere and are thus much affected by its structure. However, the studies needed to acquire detailed knowledge of lithospheric structure require large explosions, recorded by hundreds of seismograph systems. In the former Soviet Union, a series of Peaceful Nuclear Explosions (PNE) were exploded to provide such data. There have

been very few PNE in the U.S., and these experiments took place in the 1960's and 1970's long before there were large numbers of digital seismograph systems available to provide detailed recordings. These few PNE events do not provide detailed pictures of lithospheric structure and propagation of regional phases and thus cannot serve as effective benchmarks for comparison with other continents. Large chemical explosions can provide suitable sources for lithospheric experiments as proven by the EARLY RISE experiment in the Great Lakes region in the 1960's and the recent Non–Proliferation Experiment (NPE) at the Nevada Test Site. However, we have not had an opportunity to conduct a large–scale lithospheric experiment with modern equipment except with NTS sources.The Canadian geophysical community has organized to form LITHOPROBE which might be considered the modern prototype of a national effort to study the structure of the lithosphere. As part of our AFOSR funded participation in the PACE seismic project in Arizona, a Canadian group came to the experiment and brought over 200 seismic instruments. Their participation was a major key to the success of this project, and we have been searching for an opportunity to reciprocate and enhance one of their experiments. The summer of 1995 provided us such an opportunity as part of the closest thing to an PNE experiment in North America as we will see outside of NTS for the foreseeable future. This experiment was a unique opportunity to gather seismic data at regional distances with large numbers of modern seismograph systems. The recording profile extended from Alberta to New Mexico, a distance of almost 2000 km (Figure 2). In addition to the 480 instruments that we were able to bring together for the DELTA FORCE experiment last year, the 250 Canadian instruments, additions to the PASSCAL instrument pool, and instruments loaned to us from Europe brought the total number of instruments to about 750. Our effort focussed on the deep lithosphere, and Dr. Alan Levander of Rice University headed up a successful effort to obtain NSF funding for

the purpose of reversing the Canadian profile for the deep mantle phases. Our group obtained permission to fire in an abandoned uranium mine in central Wyoming which was very energetic and produced the best data from the experiment. The vast variety of seismograph systems employed made merging the data into a standard format a major task which took 9 months. We have not had time to analyze the data in detail, but the initial results are very promising. The Wyoming source produced arrivals to distances of greater than 800km (Figure 3) with charges of only 6100 kg and 6800 kg. These sources were assigned Mb magnitudes in excess of 3.0 by seismic networks in the region. This very efficient shot point was loaded using liquid explosives and a pumper truck. The maximum water depth in the mine was 55 m. The lithospheric structure as revealed by regional phases appears to vary markedly across the main tectonic boundary present which is the southern margin of the Wyoming craton. Ultimately, we will compare these data to the excellent data derived from the NPE.Initial results of the DEEP PROBE experiment show that lithospheric structure can be quite complex even in areas that are thought of as being cratonal. The effects of these complexities on regional phases can be considerable. The seismic source employed in Wyoming was very efficient and easy to load. The fact that it is still available for further studies seems like a real opportunity.

PERSONNEL SUPPORTED

The Principal Investigators on this project are G. Randy Keller, Diane I. Doser, and Kate C. Miller. In addition, the following students have been involved to a significant extent: Donald Roberts, Carlos Montana, Alejandro Duran, Donald Adams, Bashir Durrani, Raed Aldouri, Julia Whitelaw, Cathy Snelson, and Fiona Kilbride. Other students who have

worked on the project are: Jose Granillo, Jesus Chavez, Terry O'Donnell, Diana Garcia, and Claudia Campos. Donald Roberts completed his M. S. degree in May, 1993, Bashir Durrani completed his PhD. degree in December, 1993. and Donald Adams completed his PhD degree in May of 1995. Raed Aldouri and Carlos Montana are nearing completion of their Ph.D. theses. Julia Whitelaw just defended her PhD thesis, and Alejandro Duran has almost completed the final draft of his MS thesis. Cathy Snelson will use data from the DEEP PROBE experiment in a thesis.

PUBLICATIONS

Adams, D.C. and G.R. Keller, 1994, Crustal Structure and Basin Geometry in South–central New Mexico: in, G. R. Keller and S. Cather (eds), Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting, Geological Society of America, Special Paper 291, p. 241–255.

Schneider, R.V. and G.R. Keller, 1994, Crustal Structure of the Western Margin of the Rio Grande Rift and Mogollon–Datil Volcanic Field, Southwestern New Mexico and Southern Arizona: in, G. R. Keller and S. Cather (eds), Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting, Geological Society of America, Special Paper 291, p. 207–226.

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Keller, G. R., P. E. Malin, and S. D. Ruppert, 1994, Southern Sierra Nevada continental dynamics project: 1993 observations of the NPE: Proceedings, Symposium on the Non–Proliferation Experiment, Lawrence Livermore National Laboratory, p. 6.277–6.284.

Wernicke, B., R. Clayton, M. Ducea, C. Jones, S. Park, S. Ruppert, J. Saleeby, J. K. Snow, L. Squires, M. Fliedner, G. Jiracek, G. R. Keller, S. Klemperer, J. Luetgert, P. Malin, K. Miller, W. Mooney, H. Oliver, R. Phinney, and G. Thompson, 1996, Origin of high mountains in the continents: The Southern Sierra Nevada: SCIENCE, v. 271, p. 190–193

Fliedner, M. M., Ruppert, S., and the Southern Sierra Nevada Continental Dynamics Working Group, 1996, Three–dimensional crustal structure of the southern Sierra Nevada from seismic fan profiles and gravity modeling: GEOLOGY, v. 24, p. 367–370.

INTERACTIONS

Our group has maintained an active interaction with the geophysical community in regard to our project. During our experiments, we have worked with groups such as Caltech, the U. S. Geological Survey, the University of British Columbia, and Stanford University. We presented papers at the annual Seismic Research Symposia, a symposium on the Non–Proliferation Experiment, the Fall meetings of the American Geophysical Union, the Seismological Society of America annual meeting, and the annual IRIS meeting. Our DELTA FORCE and DEEP PROBE experiments received considerable attention from other groups who recorded our sources. We have interacted directly with Dr. John Cipar of the Phillips Lab in conducting broad–band seismic recording on the Colorado Plateau and in helping his group's effort as part of the DEEP PROBE experiment. Dr. H. Douglas Garbin of

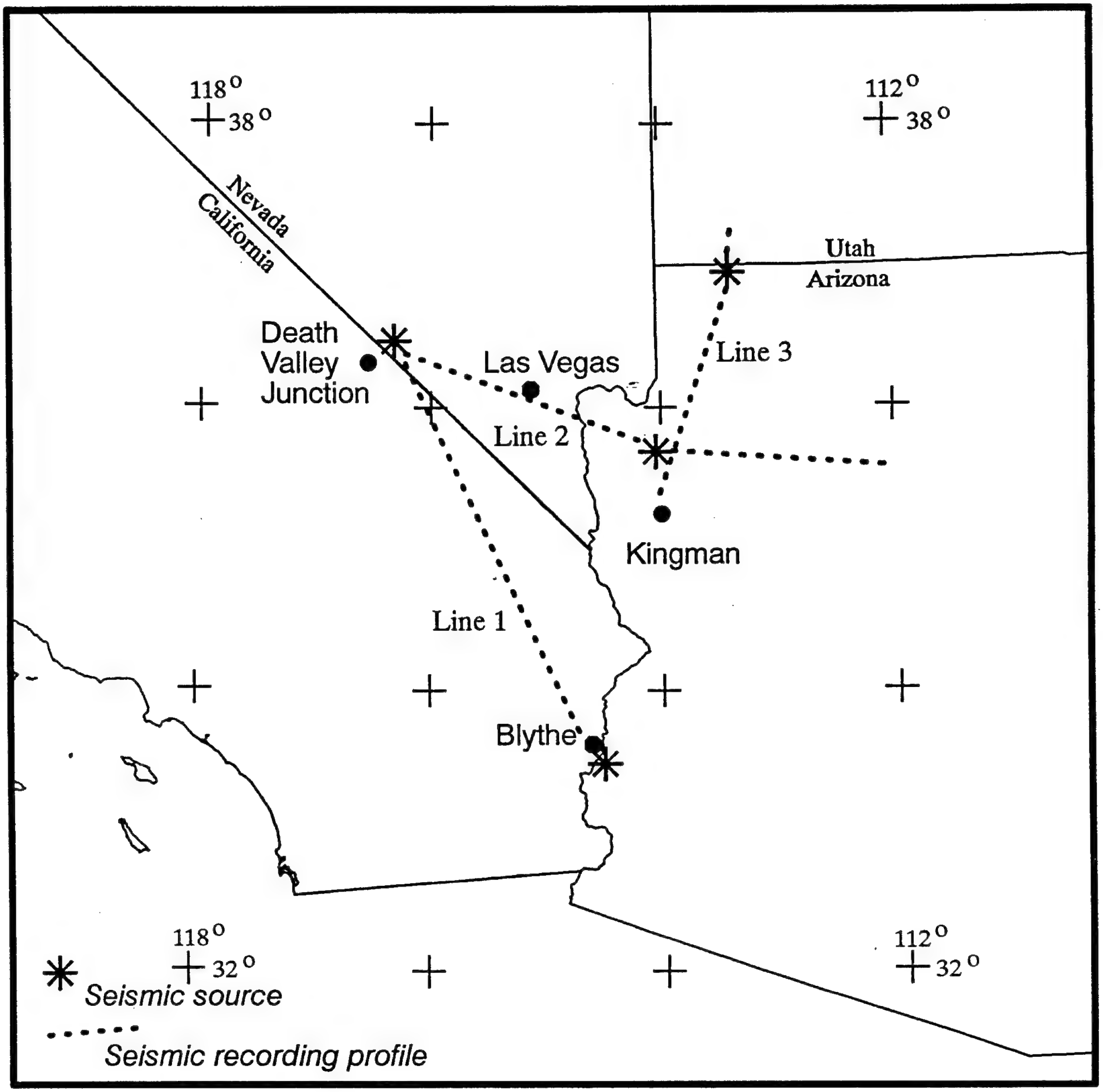
Sandia National Laboratory also used our DELTA FORCE seismic sources to conduct a study at NTS.

INVENTIONS or PATENT DISCLOSURES

None.

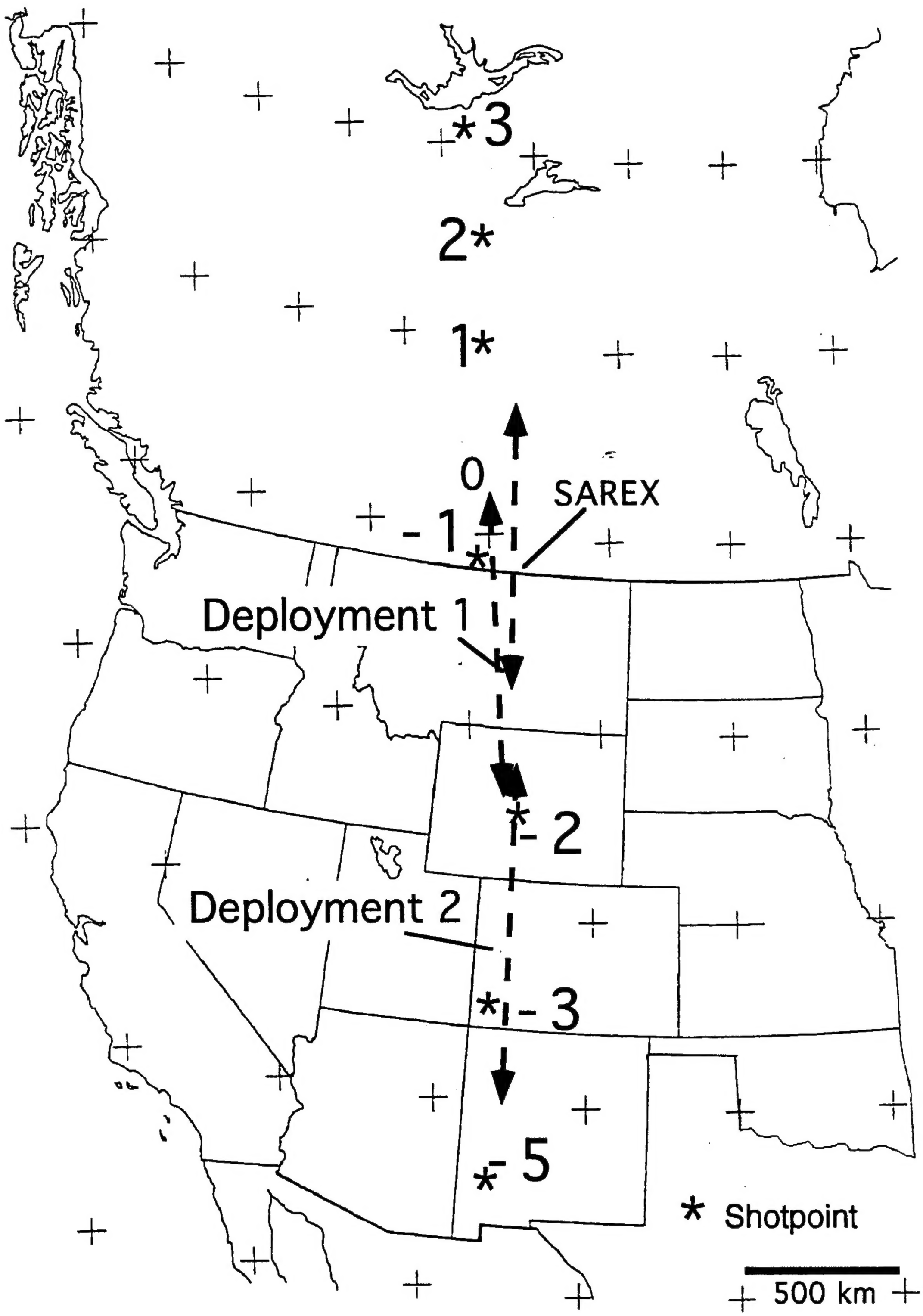
HONORS/AWARDS

G. R. Keller was elected as a Fellow of the Geological Society of America during the contract period. He had previously been elected as a Fellow of the Royal Astronomical Society.



DELTA FORCE EXPERIMENT PLAN

UTEP



Joint Canadian / US study of the mantle (Project *DEEP PROBE*)

Lead institutions: University of British Columbia, Rice University, and University of Texas at El Paso

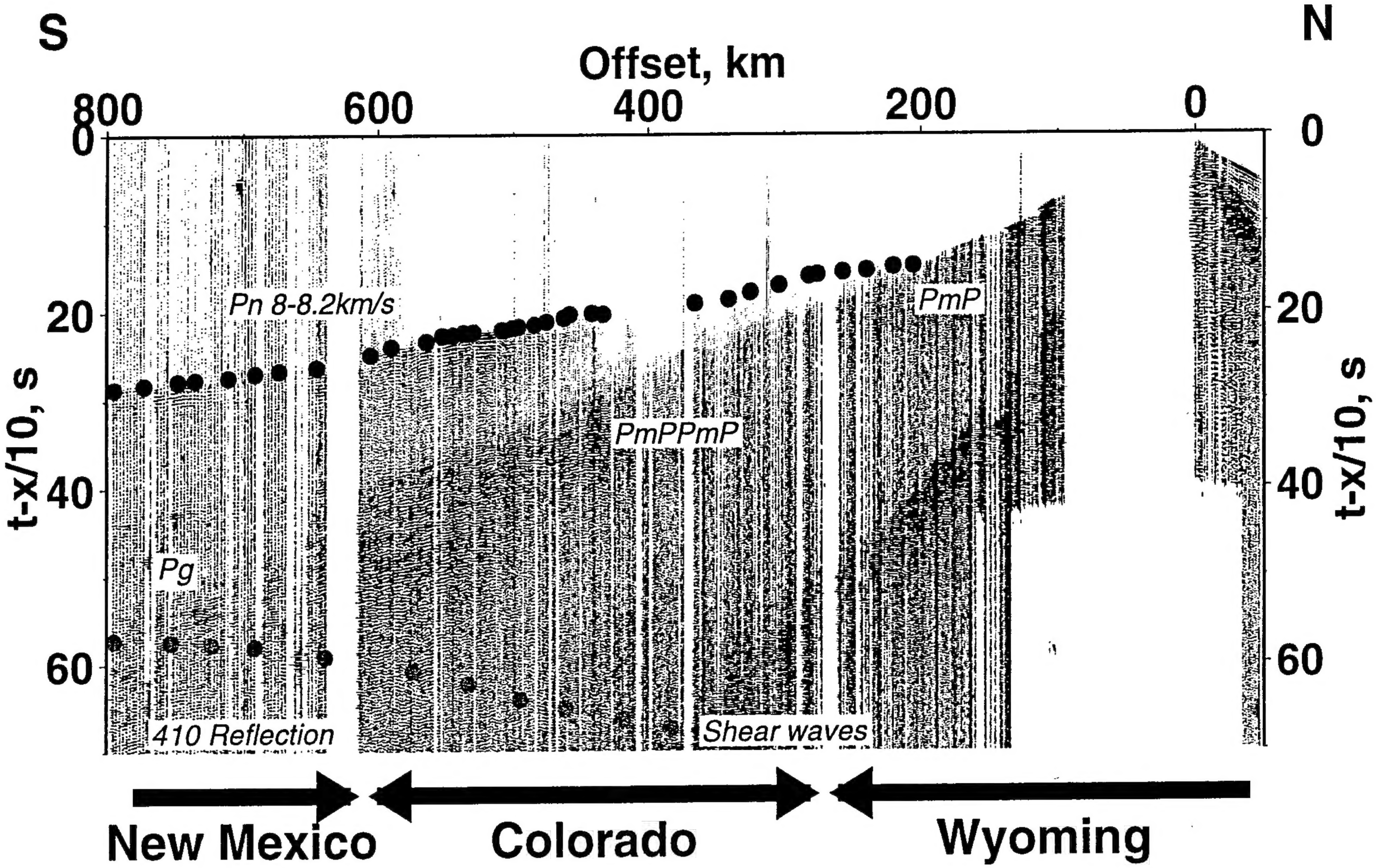
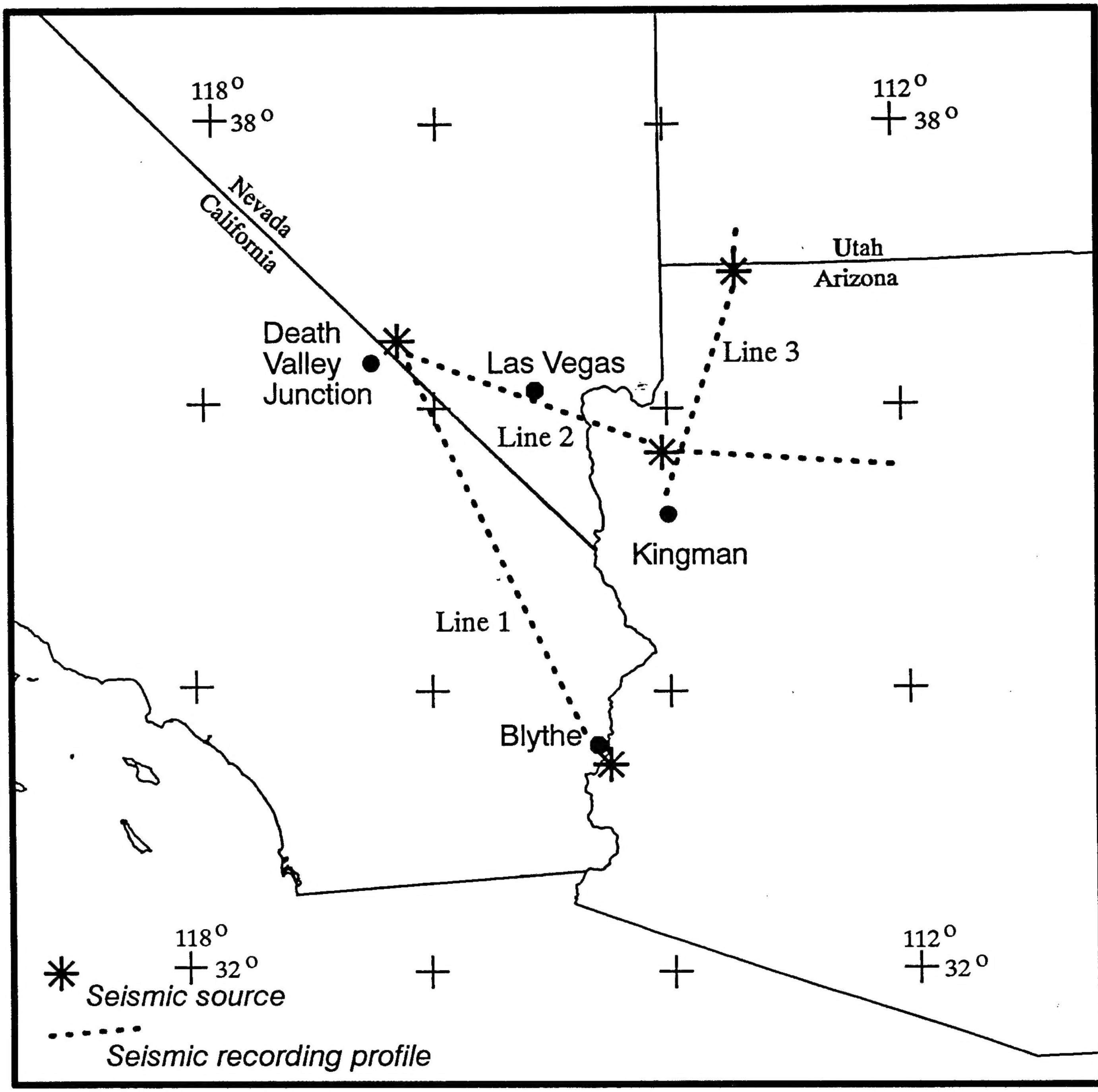
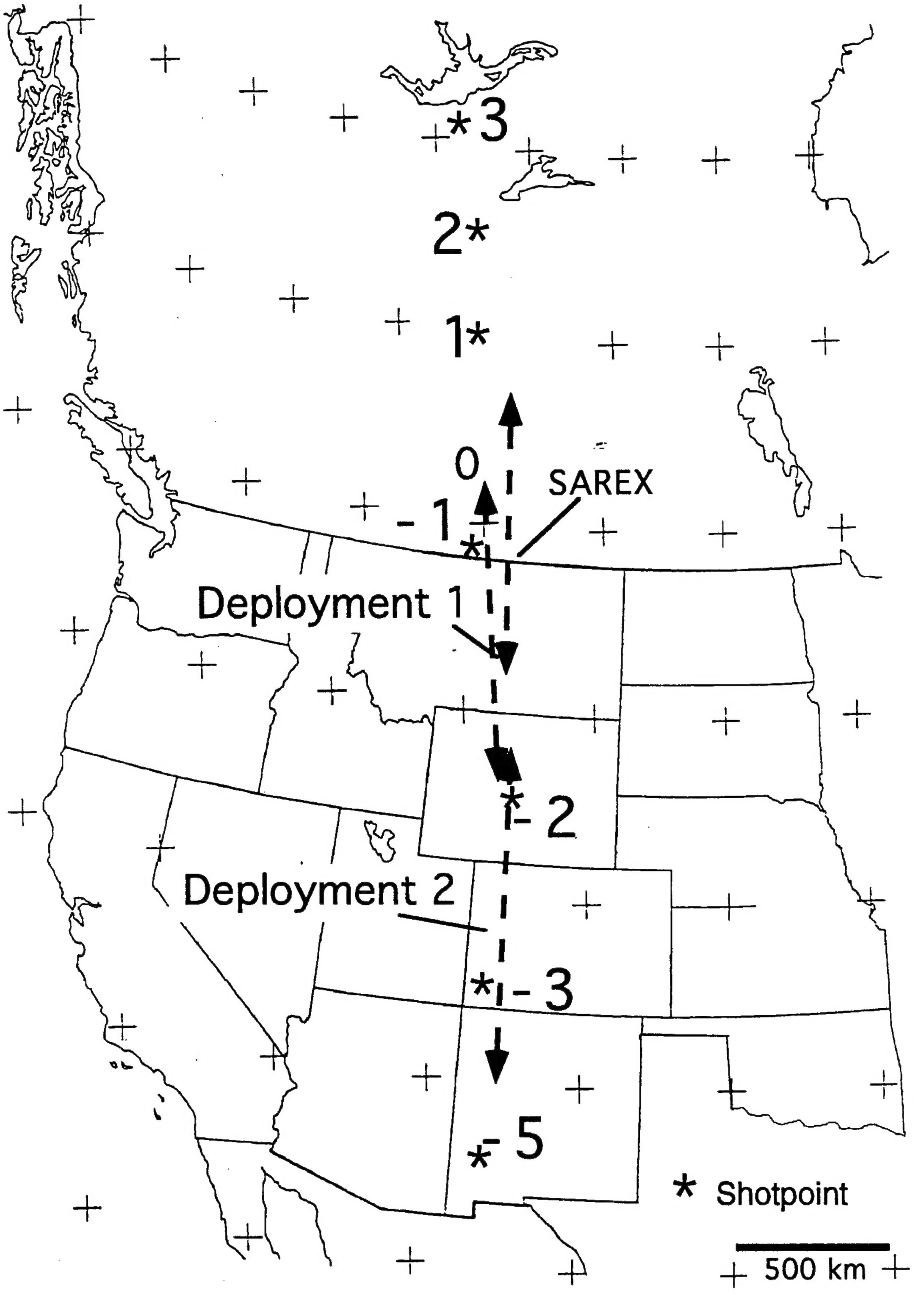


Figure 3: Record section to the south of SP 43 in southern Wyoming. Note that PmP is much slower than on the recordings north of the same shotpoint, although it is still faster than the continous band of upper crustal energy recorded out to 800 km. Between 200 km and 500 km Pn is weak, but rapidly gains in amplitude at further offsets.



DELTA FORCE EXPERIMENT PLAN

UTEP



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